# Final Technical Report (FTR)

# Earthquake Hazards Program Assistance Awards

*September 14, 2021*

- **USGS Award Number**: **G20AP00060**
- **Title of award**: **Advancement of the ISC-GEM Global Instrumental Earthquake Catalogue, 1904-2019 (Years 3)**
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- **Term covered by the award**: 06/22/2020 through 06/21/2021
- **Acknowledgement of Support and Disclaimer**

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- **Abstract**

The ISC-GEM catalogue is unique as it answers specific needs of seismic hazard research. It provides long-term, uninterrupted, and homogeneous information on moderate to large earthquakes worldwide. All earthquake parameters were re-assessed using the instrumental measurements made by analysts around the world. A large proportion of the basic information for this project was sourced from paper-based historical station bulletins and more than a thousand scientific articles. All hypocentres have been re-computed with a modern location technique and velocity model. The magnitudes are represented in the same scale, $M_W$. Each earthquake parameter (location, depth, magnitude) has an estimate of uncertainty and quality. We produced reliable $M_S$ and *mb* for many historical events; some of them never had such estimates made in the past. We also brought into digital existence historical station arrival picks, and body and surface wave amplitude measurements that were not digitally available in the past.

The ISC-GEM serves as the backbone for the historical part of the ANSS Comprehensive Earthquake Catalog (ComCat). It contributes towards the USGS seismic hazard mapping and forecasting in the US and Latin America. The catalogue helps to improve the base knowledge for calibrating the loss models used by PAGER (Prompt Assessment of Global Earthquakes for Response) to help governmental and relief agencies. Researchers in universities and commercial companies routinely use the ISC-GEM catalogue. The catalogue also contributes towards education and capacity building efforts in the developing world.

We identified several areas where the ISC-GEM catalogue needed to be further advanced. Information from recent scientific articles on current and historical earthquakes required incorporation into the catalogue. Another magnitude layer (*$M_W$ 5.0-5.5)* of potentially damaging continental earthquakes in the modern instrumental period needed to be added to the catalogue. We had to search the scientific literature for credible fault plane or moment tensor solutions. Additional measurements of arrival times and surface wave amplitudes needed to be sourced from some long-term high-quality observatories and publications to fill gaps in station reporting. This reduced the uncertainties and promoted many earthquakes from the *Supplementary* (less certain) to the *Main* part of the catalogue. Recent earthquakes also needed to be included.

Our approach was to preserve homogeneity of the ISC-GEM catalogue by applying the same production techniques used for the original version of the catalogue. The objective was to include many new earthquakes that were damaging or could have been potentially damaging and improve parameter determination of existing earthquakes. That provided more adequate representation of seismicity and associated hazard in many regions of moderate seismicity. The project resulted in the release of substantially updated version of the ISC-GEM catalogue and free availability of the added basic parametric data from the ISC.

- **Report body:**

## Objectives of the 3rd Year of the Advancement Project

Objectives of the 3rd Year of the ISC-GEM Advancement project were to:

- Recompute the surface wave magnitude MS for earthquakes with newly available data sourced from individual station bulletins. The newly available bulletins have been donated to the ISC by the archive of the University of Stuttgart (Germany);
- Regularize the magnitude cut-off, starting from earthquakes occurred since 1964. This task is particularly required considering the advances following the ISC Bulletin Rebuild Project (Storchak et al., 2017, 2020). As detailed later, during this year we focused on the period 1991-1999;
- Add continental earthquakes in the magnitude range 5.0-5.5; the time period considered this year was 1991-1999;
- Integrate source mechanisms from the literature (past and recent papers), particularly for pre-1976 earthquakes;
- Add earthquakes in 2017 based on the newly available data from the ISC Bulletin and including continental event in the magnitude range 5 to 5.5;
- Revise earthquakes already listed in previous versions of the ISC-GEM Catalogue by considering results discussed in the scientific literature (past and recent publications).

## Status of the ISC-GEM Catalogue before the beginning of the Advancement project

The state of the ISC-GEM Catalogue for the period 1904-2014 (Version 5.0, dated 27 February 2018) was summarized by Di Giacomo et al. (2018). Here we just remind that:

- the catalogue contains 35,225 earthquakes in total, with 7126 listed in the Supplementary file (about 93% of them having occurred before 1960);
- the predigital period (i.e., before 1964) is not as complete (average annual magnitude of completeness, Mc, varying between 5.7 and 6.8) as more recent decades (average annual Mc varying between 5.5 and 5.7);
- four magnitude sources are used: 1) direct Mw from GCMT (www.globalcmt.org, Dziewonski et al., 1981; Ekström et al., 2012); 2) direct Mw from the literature; 3) proxy Mw, based on our recomputed MS; 4) proxy Mw, based on our recomputed mb. The magnitude composition is 45.72% direct Mw GCMT, 42.85% Mw proxy based on MS, 8.1% Mw proxy based on mb, 3.3% direct Mw from the literature;
- source mechanisms (in form of moment tensors) are available only for earthquakes with a GCMT solution.

Starting from Version 5 of the catalogue (for a visual summary see Figure 25 of Di Giacomo et al., 2018), we detail in the following sections the tasks accomplished this year, in line with the objectives outline earlier, to advance the ISC-GEM Catalogue. The procedures adopted are the same used to produce previous versions of the catalogue and are not repeated here.

## Investigating apparent station gaps for surface wave data

In March 2019, the University of Stuttgart donated a large volume of individual station bulletins to the ISC. We are grateful for the help and support of Rudolf Widmer-Schnidrig of the Black Forest Observatory for making this possible. We digitized the readings containing amplitude and period measurements of surface waves following the same procedures described in Di Giacomo et al. (2015a). Figure 1 shows a summary of the amount of data added between 1920 and 1945. Overall, the data added is concentrated in the mid-1920s to early 1930s, and the largest contributions come from stations ALI, ALM, MAL and TOL (Alicante, Almeria, Malaga and Toledo, respectively) of the Spanish network. Notable additions are also readings from non-European stations, such as USA stations CHK and HON (Chicago and Honolulu, respectively) as well as Japanese stations KOB and SUM (Kobe and Sumoto, respectively). Only station Sofia (SOF, Bulgaria), has been added in the early 1940s.

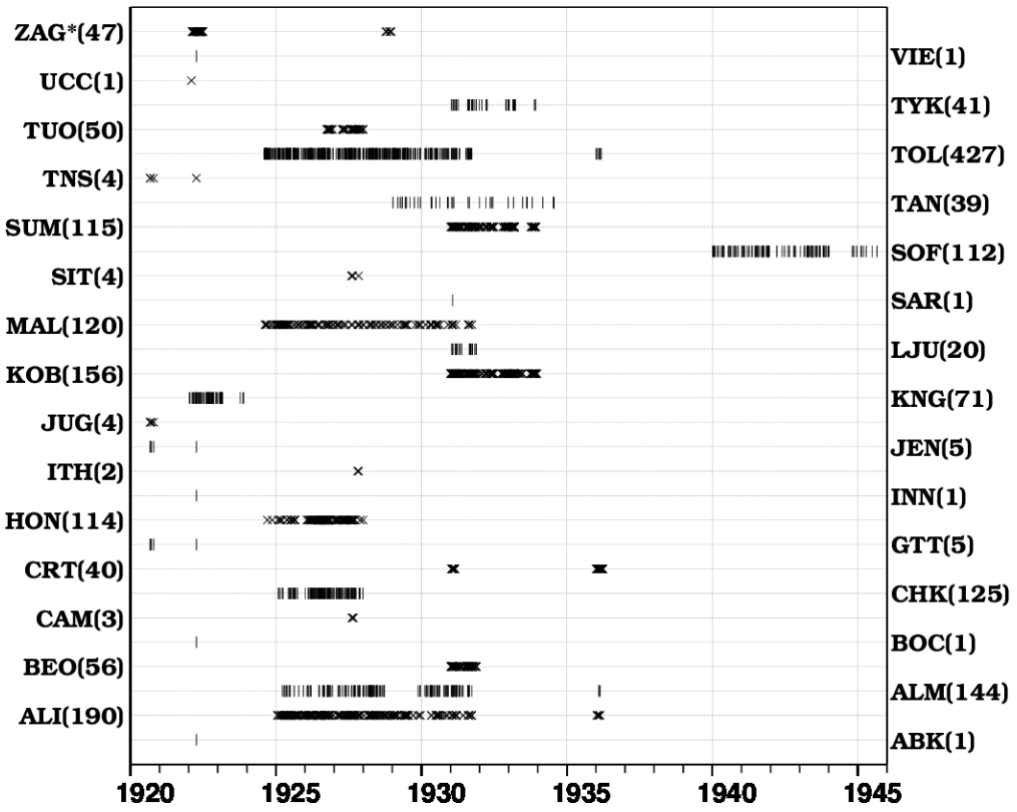


***Fig. 1****: Timeline of the readings added from the individual station bulletins received from the archive of the University of Stuttgart thanks to the cooperation of Rudolf Wiedmer-Schnidrig. Each symbol (vertical dash for station codes on the right-hand side, crosses for station codes on the left-hand side) is the initial time of a reading associated to an earthquake. The total number of readings added for each station is shown in brackets.*

Such bulletins fill important gaps in our existing inventory, and we aimed at adding data for any earthquake already in the ISC-GEM Catalogue as well as earthquakes not selected before for lack of amplitude stations. In total, we added ~1900 readings from 30 stations associated to ~900 earthquakes in the ISC-GEM Catalogue and over 80 earthquakes not included in the catalogue. Such bulletins proved to be a significant asset to strengthen the magnitude estimations for these earthquakes. Figure 2 shows the histogram distribution of the number of stations (NSTA) contributing to MS in the previous version of the ISC-GEM Catalogue and to the MS reassessed after adding the data sourced from the bulletins donated by the University of Stuttgart.

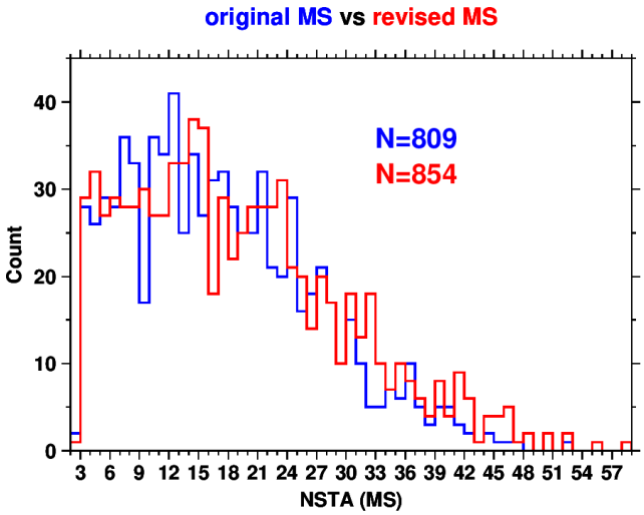


***Fig. 2**: Number of stations (NSTA) contributing to MS in the previous version of the catalogue (blue) and with the newly added data (red).*

The most important effect in the increase in NSTA is the gain of 45 new MS values for earthquakes that we did not have any. As a result, 36 earthquakes previously listed in the supplementary file now are listed in the main catalogue (9 earthquakes have uncertain magnitude and are still listed in the Supplementary file). In general, marginal changes affect the MS of the earthquakes with revised MS (Figure 3).

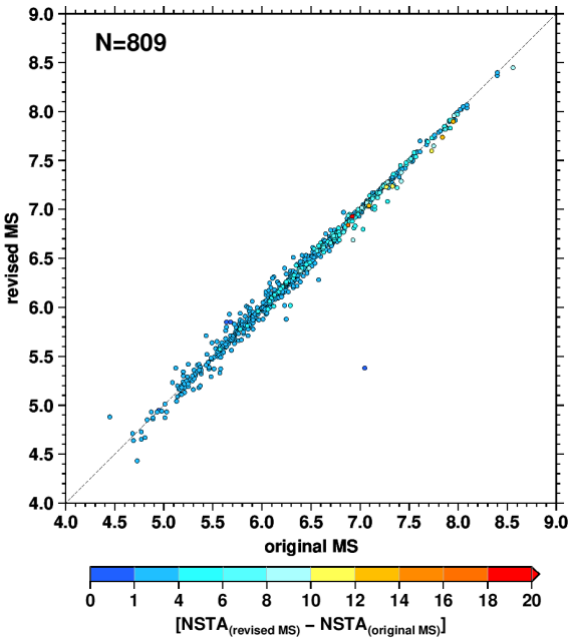


***Fig. 3**: Comparison of the original and revised MS for the earthquakes with data added from the bulletins of the University of Stuttgart.*

The most notable exception is event 907055, where we observe a large change in MS from 7.05 to 5.38. This event is part of an aftershock sequence in the Bougainville – Solomon

Islands region during October 1931 and two readings, one from UPP (Uppsala, Sweden) and the other from Gottingen (GTT, Germany), were wrongly associated to evid 907055 instead of larger events close to evid 907055. After reassociating UPP and GTT readings to the correct events, we obtain a new MS of 5.4 for evid 907055 thanks to the readings added from SUM and KOB station bulletins.

Another benefit of the data added from the bulletins of the University of Stuttgart regards the improvements in location (the readings added may also contain body-wave arrival times). We have updated the location flag from D to C for four earthquakes (evid 909834, 910109, 909037 and 907067) thanks to the additional arrival times we have digitized whilst searching for surface wave data. Of the 900 reprocessed earthquakes only 11 earthquakes (evid 912640, 911049, 910668, 911221, 910345, 908669, 908792, 910670, 909834, 909037 and 907067) were affected by significant changes in epicentre (more than 100 km) and/or depth (more than 20 km).

As previously mentioned, on top of the events already listed in the catalogue, we also added data for earthquakes that were not selected due to lack of amplitude stations. Of the 80 earthquakes with new data we added to the catalogue 17 events. We have obtained magnitude for the first time for evid 912005, 912028, 910419, 909879, 909965 (the largest event is an MS 6.5 in Northern Xinjiang in 1922, evid 912028), whereas evid 910549 and 906674 have no magnitude and evid 909751, 909935, 906908, 905422 and 905423 have highly uncertain magnitude. Finally, evid 911824, 910660, 909793, 909954 and 907104 have poor location (location quality flag set to D, hence these events are listed in the supplementary file of the catalogue).

## Regularizing the cut-off magnitude

For earthquakes occurred since 1964 the original selection was based on the magnitude information available at the time of the first release in 2013 (Storchak et al., 2013). Since then we improved the overall status of the ISC Bulletin (www.isc.ac.uk/iscbulletin/) thanks to the ongoing Rebuild work of the ISC Bulletin (Storchak et al., 2017). The improvements regard both location and magnitude parameters within the ISC Bulletin as the ISC was able to use additional datasets and more robust review procedures. This gives us the opportunity to add earthquakes that were not selected in the first release since the magnitude information was not considered reliable (e.g., magnitudes based on less than 3 stations). Hence, with this task we aim at regularizing the content of the catalogue toward the lower magnitude end (original cut-off magnitude of 5.5 from the 1960s onwards) by adding global earthquakes that, in light of the latest results based on the data available, should be added to the ISC-GEM Catalogue. By doing so we also expect to marginally improve the Mc over recent decades.

As the rebuild project is not finished yet, we focused on 1991-1999 for the current project year. This is the last period to cover for this task.

Thanks to the improved magnitude procedure introduced at the ISC (Bondár and Storchak. 2011), we searched for earthquakes in 1991-1999 not selected before having magnitude (direct or proxy Mw) > 5.45. Figure 4 summarizes the earthquakes finally added to the ISC-GEM Catalogue to regularize the cut-off magnitude during 1991-1999. The global

maps in Figure 4 show how most of the earthquakes added within this task are located along major plate tectonic boundaries and mid-oceanic ridges.

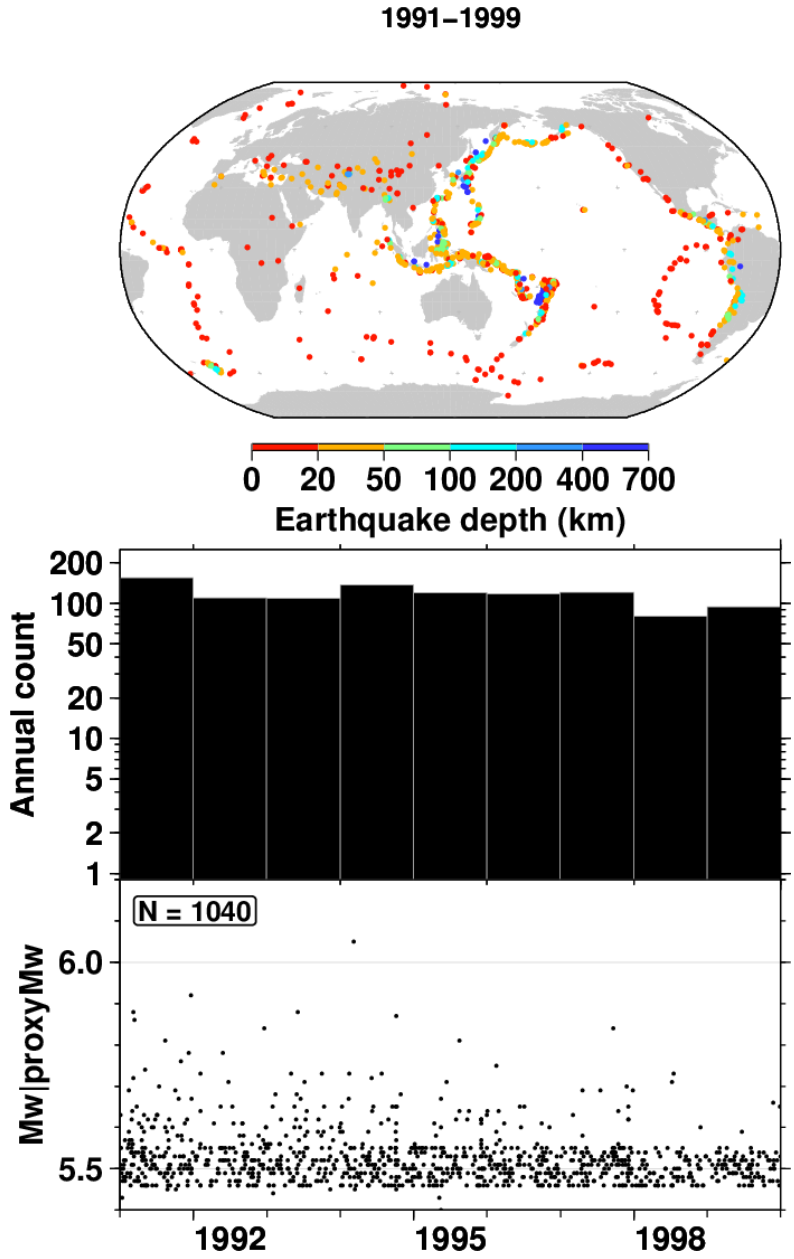


***Fig. 4**: Top: global distributions of the earthquakes added during 1991-1999 to regularize the cut-off magnitude threshold. Bottom: magnitude timelines along with their annual counts.*

## Continental earthquakes

Moderate shallow continental earthquakes are important for hazard studies as they can cause significant damage in populated areas. For this reason, in the Advancement project we add shallow earthquakes occurring in main land masses by dropping the magnitude cut-off threshold down to 5.0. It is important to remind that the magnitude reliability usually

deteriorates when considering earthquakes below magnitude 5.5, especially for those events without a direct Mw that occurred between the 1960s and 1990s (i.e., before the expansion of the station global network we can process over the last ~20 years).

The definition of continental earthquakes is not uniquely defined in the seismological community. For the purposes of the ISC-GEM Catalogue, we consider as continental earthquakes shallow (depth down to 60 km) events that occurred in the main continental masses of Africa, Eurasia, Americas, and Australia. Hence, with this approach, we exclude events occurring in the islands of the Pacific Ocean. Figure 5 shows the continental earthquakes finally added to the ISC-GEM Catalogue during 1991-1999. T is the last modern period we had to process for this task ton include continental earthquakes from 1964 onwards.

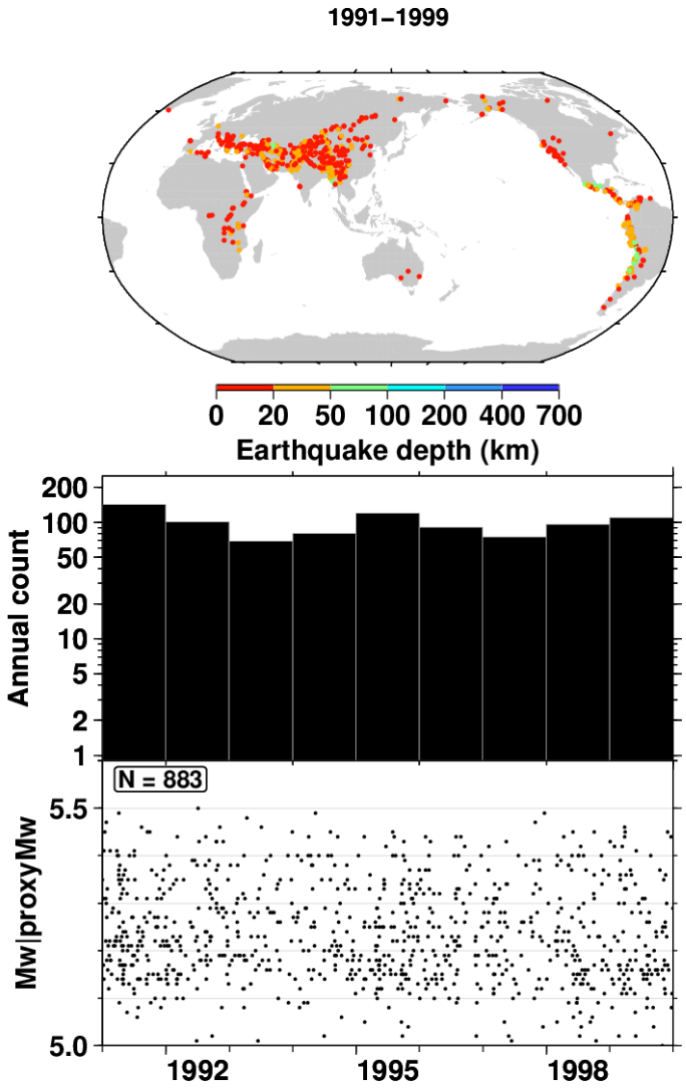


***Fig. 5****: As for Fig. 4 but for continental earthquakes. See text for details.*

The global map of Figure 5 highlights how most of the continental earthquakes are in Eurasia. However, a significant number of events is also added in Africa and parts of the Americas.

## Earthquakes in 2017

The update of the ISC-GEM Catalogue for recent years benefits from the data collected and reviewed by ISC analysts to produce the ISC Bulletin (www.isc.ac.uk/iscbulletin). As for 2015 and 2016, we selected global earthquakes with magnitude 5.5 and above and, in addition, added continental events (as defined earlier) with magnitude between 5.0 and 5.5. In total, we added 543 earthquakes in 2017, 135 of which are from continental areas. For 45 earthquakes we obtained Mw from our recomputed mb/MS following the same procedures adopted in previous version of the ISC-GEM Catalogue (Di Giacomo et al., 2015b). These earthquakes with Mw proxy are often aftershocks of significant earthquakes. The results regarding 2017 will be included in the section describing the new version of the ISC-GEM Catalogue.

## Direct $M_0$ and source mechanisms from the literature

Following the work by Lee and Engdahl (2015), we started to expand the bibliographic search of reliable seismic moments $M_0$ (and, therefore, of Mw) to also include source mechanisms from the literature. With source mechanism here we refer either to the six moment tensor elements and/or fault plane solutions (nodal planes described by strike, dip and rake angles). In Version 5 of the ISC-GEM catalogue we included a total of 981 direct $M_0$ from the literature selected from about 250 different publications. The earthquakes in the catalogue files having $M_0$ from the literature are identified by the value *bibliog* in the *mo_auth* field. The list of earthquakes with $M_0$ from the literature and corresponding reference source is available at www.isc.ac.uk/iscgem/mw_bibliography.php.

The $M_0$ from the literature is particularly important for earthquakes before the GCMT solutions became available for global earthquakes in the late 1970s. However, due to time and resource limitations, the literature was consulted only to retrieve reliable values of $M_0$, even though other relevant results were available, such as source mechanisms. With the Advancement project we started to check the papers used to retrieve direct values of $M_0$ and add, if available and considered reliable, source mechanisms for earthquakes without a GCMT solution. As it will be discussed later, when checking a paper, we did not limit to look for source mechanisms, but we considered various aspects of the results published in a paper concerning earthquakes in the ISC-GEM catalogue. Thus, we used this opportunity also to cross-check our location results (especially depth) with the findings of authors making detailed studies for specific earthquakes or areas. During this task we did not limit to check only the papers considered by Lee and Engdahl (2015) but expanded the literature search to other publications (past and recent) to include new values of direct $M_0$ for earthquakes which were listed in the catalogue with a proxy Mw. This task applies both to earthquakes already listed in Version 5 of the ISC-GEM Catalogue and to earthquakes added during the Advancement project.

In this project year, we checked the results in about 200 papers which consider over 500 earthquakes in total and added for the first time direct $M_0$ values from the literature for 322 earthquakes (details for individual earthquakes to be outlined in the next section). Considering that it may be possible to obtain $M_0$ without a (reliable) source mechanisms,

we finally accepted and added source mechanisms for 448 earthquakes, as summarized in Figure 6.

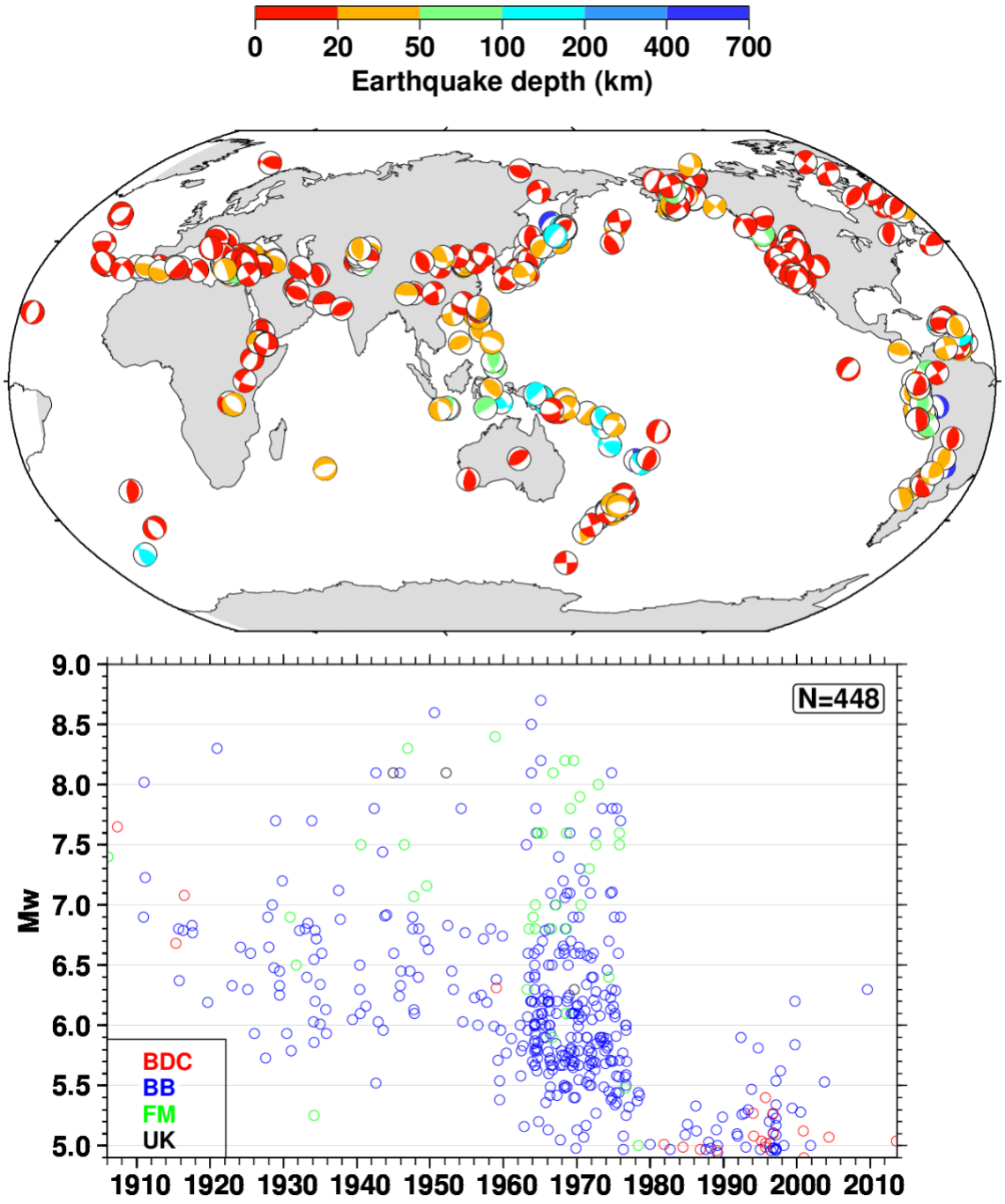


***Fig. 6**: Top: global map showing the distribution of the 448 earthquakes with source mechanism added from the literature. The source mechanisms are color-coded by depth.*

*Bottom: timeline color-coded by source mechanism type: red = best double couple; blue = broadband analysis (BB); green = first motion polarities (FM); black= unknown (UK).*

The source mechanisms added this year are largely in the 1960s-1970s and, for the first time in the ISC-GEM Catalogue, also for earthquakes in recent decades (i.e., after GCMT started in 1976).

This task greatly benefitted from the work by the ISC to maintain the Event Bibliography (http://www.isc.ac.uk/event_bibliography/index.php, for more details see Di Giacomo et al., 2014). We will continue to monitor new publications for updating or adding $M_0$ and source mechanisms from the literature, but with this year project we finished searching in the past literature.

## Revision of earthquakes already listed in previous versions and updates

As mentioned earlier, during the review of the literature we cross-checked our results with those available in the detailed studies from different authors. When needed, we reprocessed events already listed in previous versions to improve location/depth and/or magnitude. In this year project we reprocessed about 400 earthquakes for this task, and the changes are detailed below.

- Updated location/depth/magnitude for the following earthquakes:
    - from Cara et al. (2017), evid = 610326285 has a direct Mw = 5.3 instead of a proxy Mw = 5.8;
    - from Okal (1992), evid = 16957884 has a direct Mw = 8.45±0.3 instead of a proxy Mw = 8.75±0.7. The seismic moment of Okal (1992), although adjusted and based on a single station (UPP), is in line with the Mw estimations of 8.3-8.6 from more recent literature. This Mw value is also consistent with results from tsunami studies (see references in the Event Bibliography);
    - from Ayele and Kulhánek (2000), evid 16957915, 16958124 and 908452 have direct Mw = 6.5, 6.9 and 6.7 instead of proxy Mw = 6.5, 7.3 and 6.9, respectively. The locations have also been updated in line with the results of Ayele and Kulhánek (2000): evid 16957915, 16958124, 908452 moved about 220 km to the East, 130 to NNW and 50 km to the West, respectively. Source mechanisms added as well;
    - from Huang et al. (1998), added direct Mw for evid 914265, 913894, 913818, 881210. All four deep events are not listed in the main catalogue with Mw between 6.3 and 7.6. Source mechanisms added as well;
    - Evid = 913877 has been relocated about 32 km to the West with fixed depth of 15 km instead of 35 km;
    - Evid 16958205 has been relocated about 43 km NNE taking into account the results in the literature. Its large aftershock, evid = 610326388, has also been relocated about 30 km NNE;
    - from Kulikova et al. (2016), evid = 16958134 has a direct Mw = 7.2 instead of a proxy Mw = 7.3. Source mechanism added as well;
    - Evid 912192 has been relocated about 124 km South with fixed depth of 65 km instead of 15 km;

- from Ou et al. (2020), evid = 912687 has an updated direct Mw = 7.9 instead of direct Mw = 8.3 from Chen and Molnar (1977). Source mechanism added as well. The location has also been updated 35 km South of previous location after adding 33 body-wave arrival times from stations located in Germany;
- from Doser et al. (2005), added direct Mw for evid 913947, 913793, 913579, 912920, 909422, 907465, 902017, 899948. Evid 913793 now is listed in the main catalogue with Mw = 6.8, whereas for the other seven events the magnitude change is within 0.1 or 0.2 magnitude units. Source mechanisms added as well;
- from Doser et al. (1999), added direct Mw for evid 912127, 908156, 908161, 908162, 898072, 897342 and 874715. Evid 908161 has been relocated 40 km South and with fixed depth of 15 instead of 65 km. Evid 908156 and 898072 are now listed in the main catalogue with Mw = 6.25 and 6.13, respectively. The magnitude changes for the other events are all within 0.3 magnitude units but for evid 874715 (direct Mw = 5.6 instead of proxy Mw = 6.0). Source mechanisms added as well;
- from Doser and Webb (2003), added direct Mw for evid ;913599, 906608, 900403, 898007, 887887 and 600678247. Evid 900403 has been relocated 100 km North and now is listed in the main catalogue with Mw = 5.5 The magnitude changes are all within 0.2 magnitude units. Source mechanisms added as well;
- from Fernández-Arce and Doser (2009), evid = 910853 has a direct Mw = 6.65 instead of a proxy Mw = 7.13. The location of the event has also been updated taking into account the discussion in Fernández-Arce and Doser (2009) and references therein. The fixed depth is now 25 km (instead of 15 km) and epicentre about 56 km Southwest of previous location. Source mechanism added as well;
- Evid = 903992 has been relocated 89 km SSW of previous location and fixed depth updated from 35 km to 15 km;
- from Doser (1989a), added direct Mw for evid 910562, 904601, 904621, 898156, 882681 and 863737. The magnitude changes are within 0.3 magnitude units. Source mechanisms added as well;
- from Fletcher and Christensen (1996), evid 903173, 898078 and 884131 have direct Mw = 7.12, 7.07, 6.80 instead of proxy Mw = 7.12, 7.15, 7.12, respectively. Source mechanisms added as well;
- from Doser and Brown (2001), added direct Mw for evid 908754, 906081, 905539, 904918, 904995, 900071, 898216, 896889, 891130 and 872100. The latter is now listed in the main catalogue with Mw = 6.07. These events have occurred between 1928 and 1963 in the Prince William Sound, Alaska, region and have Mw between 6.0 and 7.0. The largest magnitude changes occur for evid = 904995 (direct Mw = 6.7 instead of proxy Mw = 6.0), evid 900071 (direct Mw = 6.9 instead of proxy Mw = 7.3) and evid = 891130 (direct Mw = 6.8 instead of proxy Mw = 6.4), whereas for the other six earthquakes the magnitude changes are within 0.15 magnitude units. Source mechanisms added as well;
- from Coudurier-Curveur et al. (2020), evid = 895681 has an updated direct Mw = 8.7 instead of a direct Mw = 8.6 from Kanamori (1977). Source mechanism

added as well;

- Evid = 895647 is listed in the Main Cataogue after updating the depth to 15 km (instead of 125 km) that allowed us to obtain a proxy Mw = 5.8 based on MS from 15 stations;
- Evid = 894262 has an updated proxy Mw = 6.9 instead of proxy Mw = 7.1. The new proxy Mw is based on MS from 27 stations instead of 10;
- from Alvarado and Beck (2006), evid = 899270 and 893012 have direct Mw = 6.9 and 6.8 instead of proxy Mw = 7.2 and 6.5, respectively. Source mechanisms added as well;
- from Doser (2005), added direct Mw for evid 904937, 900732, 900577, 899178, 893820, 891517, 890763, 886362, 875994, 872296, 872570. These events have occurred between 1934 and 1963 in the Kodiak Island region and have Mw between 5.9 and 6.7. The largest magnitude changes occur for evid = 900732 (direct Mw = 6.2 instead of proxy Mw = 6.6), evid 893820 (direct Mw = 6.45 instead of proxy Mw = 6.85) whereas for the other nine earthquakes the magnitude changes are within 0.3 magnitude units. Evid 900577 has also been relocated about 27 km S-SW of previous location and depth updated from 35 km to 90 km. Source mechanisms added as well;
- from Okal and Saloor (2017), evid 897790 and 897857 have updated direct Mw = 7.7 and 7.6, respectively, instead of direct Mw = 7.0 from Doser and Webb (2003), and proxy Mw = 7.14, respectively. Also the locations have been revised following Okal and Saloor (2017) and references therein: evid = 897790 has the epicentre about 60 km NNE from previous location and fixed depth = 15 km (instead of 25 km); evid = 897857 has the epicentre about 68 km to the East from previous location;
- from Doser (1990), evid 897809 has direct Mw = 6.45 instead of proxy Mw = 6.56. Source mechanism added as well;
- from Başarır Baştürk et al. (2016), evid 873085 has an updated direct Mw = 6.14 instead of direct Mw = 6.2 from North (1977). Evid 904020 and 904023 have an updated direct Mw = 6.34 and 6.0, respectively, instead of proxy Mw = 6.37 and 6.35, respectively. Source mechanisms added as well;
- from Melis et al. (2020), evid = 896705 as a direct Mw = 7.16 instead of a proxy Mw = 6.54. Source mechanisms added as well;
- from Doser et al. (1999), added direct Mw for 17 earthquakes in the Prince William Sound region (evid 869987, 870100, 870148, 868333, 868342, 868414, 868951, 868977, 867811, 864430, 845076, 814226, 809082, 792985, 757785, 756140, 732776). The magnitude changes are all within 0.4 magnitude units but for evid = 868951 (direct Mw = 6.4 instead of proxy Mw = 5.75), evid 868333 (direct Mw = 6.42 instead of proxy Mw = 5.90) and evid 867811 (direct Mw = 5.67 instead of proxy Mw = 6.13). Source mechanisms added as well;
- from Doser et al. (2002), added direct Mw for 18 earthquakes in the Kodiak island region (evid 870136, 868351, 868363, 868783, 865396, 856357, 853605, 851909, 851097, 848441, 848633, 824251, 797882, 796868, 757502, 750989, 738145, 738149). These events have occurred between 1965 and 1974 in the Kodiak Island region and the magnitude changes are all within 0.4 magnitude units. Source mechanisms added as well;

- from Patton and Zandt (1991), added direct Mw for evid 875624, 851116, 829986, 824428, 818715, 724791 and 592538. The magnitude changes are within 0.5 magnitude units. Source mechanisms added as well;
- from Assumpção and Araujo (1993), added direct Mw for evid 851422, 837096, 807188, 703930 and 654584. Evid 851422 is now listed in the main catalogue. The magnitude changes are all within 0.2 magnitude units but for evid = 654584 (direct Mw = 5.0 instead of proxy Mw = 5.5). Source mechanisms added as well;
- from Frankel (1984), evid = 651770 has direct Mw = 4.9 instead of proxy Mw = 5.3;
- from Webb and Anderson (1998), added direct Mw for evid 848946, 822768, 752113 and 727299. The magnitude changes are all within 0.2 magnitude units. Source mechanisms added as well;
- from Wei and Chung (1993), evid 749631 and 458848 have direct Mw = 5.2 and 5.0, respectively, instead of proxy Mw = 5.3. Source mechanism added for evid 458848;
- from Bent and Hasegawa (1992), evid 410206 has direct Mw = 5.0 instead of proxy Mw = 5.4. Source mechanisms added as well;
- the direct Mw = 5.7 from Westaway (1990) for the 1974-09-04 Tripoli, Libya, event was erroneously associated to evid = 737146 instead of evid = 737147. Evid = 737146 has now a proxy Mw = 5.6 based on our re-computed mb;
- from Doser and Vandusen (1996), added direct Mw for evid 909727, 904192, 901464, 881160, 908913, 899241, 887289 and 879338. The first four events were listed in the Supplementary catalogue and are now listed in the Main Catalogue with Mw between 5.9 and 6.6, whereas the last four events have Mw between 5.8 and 6.3 instead of proxy Mw between 5.8 and 6.5. Evid = 879338 has also been relocated about 9 km N-NE of previous location. Source mechanisms added as well;
- Evid = 909960 has an updated location about 29 km NNW of previous one and depth = 10 km instead of 15 km. The updated location is consistent with the results of Amorèse et al. (2020). Our proxy Mw = 5.0, although within the Mw range of 5.0-5.5 estimated by Amorèse et al. (2020), is based on a poorly constrained MS, and the event is still listed in the Supplementary catalogue;
- Evid 895280, 895549 and 895717 have updated Mw proxy = 6.8, 6.6 and 6.3 instead of 6.7, 6.3 and 6.4, respectively, after MS recomputations thanks to amplitude reading added from European stations;
- from Doser (1987), evid 881629 and 882314 have direct Mw = 5.7 and 5.5 instead of proxy Mw = 6.0 and 5.6, respectively. Evid = 882316., previously in the supplementary catalogue, has now a direct Mw = 5.4. Source mechanisms added as well;
- from Doser et al. (1997), added direct Mw for evid 885173, 799398, 796590, 796787 and 796899. These events have occurred between 1958 and 1970 in the Yakutak block, Alaska, and the magnitude changes are all within 0.3 magnitude units. Source mechanisms added as well;
- from Okal (2012), evid 903272 and 899940 have direct Mw = 6.9 and 7.4 instead of proxy Mw = 6.9 and 7.0, respectively. Source mechanisms added as

well;

- from McCaffrey (1993), evid = 901916 has direct Mw = 7.83 instead of proxy Mw = 7.95;
- from Bent (2002), evid = 905919 has an updated direct Mw = 7.44 instead of a direct Mw = 7.7 from Stein et al. (1979). Source mechanisms added as well;
- from Doser (1988), evid 904767 has direct Mw = 6 instead of proxy Mw = 6.5 and source mechanism added. Evid 904766 and 899958, previously in the supplementary catalogue, have direct Mw = 5.6 and are now listed in the main catalogue;
- from Doser (1989b), evid 904837 and 904838 have direct Mw = 6.56 and 5.86 instead of proxy Mw = 6.55 and 6.05, respectively. Source mechanisms added as well;
- from Abe (1978), evid = 904853 has a direct Mw = 5.25 instead of a proxy Mw = 5.57. Source mechanism added as well;
- from Cassidy and Bent (1993), evid = 901383 has a direct Mw = 6.3 instead of a proxy Mw = 6.23. Source mechanism added as well;
- from Baker et al. (1997), evid 883288 and 754132 have direct Mw = 6.74 and 5.8 instead of proxy Mw = 6.65 and 5.78, respectively. Evid 873781, 868700, 855169 and 835092 have updated direct Mw = 5.5, 5.7, 6.1 and 5.9, respectively, instead of direct Mw = 5.7, 6.0, 6.3 and 6.2, respectively, from North (1977). Source mechanisms added as well;
- from Anderson et al. (1993), added direct Mw for evid 857649, 848647, 822588, and 817350. These events have occurred between 1964 and 1971 in South Island, New Zealand, and the magnitude changes are all within 0.2 magnitude units. Source mechanisms added as well;
- from Malavé and Suárez (1995), evid 815159 has direct Mw = 5.9 instead of proxy Mw = 6.1. Source mechanisms added as well;
- from Kanamori et al. (2019), evid = 879136 has an updated direct Mw = 9.55 instead of direct Mw = 9.6 from Cifuentes and Silver (1989). A source mechanism with strike-slip component (rake = 140°) has also been added. However, as noted by Kanamori et al. (2019), other solutions are possible;
- from Kanamori and Rivera (2017), evid = 879416 has an updated direct Mw = 7.7 instead of a direct Mw = 7.8 from Kanamori and Stewart (1976);
- from Huang et al. (1986), evid = 874839 and 774087 have direct Mw = 5.8 and 5.7 instead of a proxy Mw = 5.76 and 5.42, respectively. Source mechanisms added as well;
- from Wallace et al. (1981), evid = 875249 and 731708 have direct Mw = 5.8 and 6.0 instead of proxy Mw = 5.9 and 6.0, respectively. Source mechanisms added as well;
- from Kiratzi and Langston (1989), evid = 773147 has direct Mw = 6.21 instead of proxy Mw = 6.27. Source mechanism added as well;
- from Taymaz et al. (1991b), evid = 866809 and 784837 have direct Mw = 5.8 and 6.58 instead of a proxy Mw = 5.82 and 6.86, respectively. Source mechanisms added as well;
- from Papadimitriou (1993), evid = 806820, 769484 and 754939 have direct Mw = 5.65, 6.2 and 5.7, respectively, instead of proxy Mw = 5.55, 6.4 and 5.9,

respectively. Source mechanisms added as well;

- from Taymaz et al. (1990), evid 857618, 847303 and 807959 have updated direct Mw = 6.0, 5.5, 6.0, respectively, instead of direct Mw = 6.2, 6.0 and 6.1, respectively, from North (1977). Evid 724259 has direct Mw = 5.57 instead of a proxy Mw = 5.54. Source mechanisms added as well;
- from Lyon-Caen et al. (1988), evid = 858076 has an updated direct Mw = 5.5 instead of direct Mw = 6.1 from North (1977). Source mechanism added as well;
- from Kao et al. (2000), added direct Mw for 17 earthquakes in the Luzon arc – Taiwan region (evid 864850, 858396, 843541, 837387, 826743, 804142, 784309, 779458, 776783, 777303, 772321, 769785, 763903, 747879, 735580, 683487, 145772). The magnitude changes are all within 0.4 magnitude units but for evid = 826743 (direct Mw = 6.66 instead of proxy Mw = 7.14), evid 769785 (direct Mw = 5.85 instead of proxy Mw = 6.36) and evid 843541 (direct Mw = 5.63 instead of proxy Mw = 6.19). Source mechanisms added as well;
- Evid = 939317 has an updated proxy Mw = 5.7 based on mb instead of proxy Mw = 6.3 based on MS;
- from Morelli et al. (2000), evid = 1047337 has an updated direct Mw = 5.6 instead of a proxy Mw = 5.8. Source mechanisms added as well;
- from Craig et al. (2011), evid 1675144 has an updated direct Mw = 5.2 instead of a proxy Mw = 5.6. Source mechanisms added as well;
- from Chi and Dreger (2004), evid 1656084 and 1656086 have updated direct Mw = 5.8 and 6.2, respectively, instead of proxy Mw = 6.3 and 6.4, respectively. Source mechanisms added as well;
- from Fan et al. (1994), evid 776886 has an updated direct Mw = 5.7 instead of a proxy Mw = 5.7. Evid 738538 has an updated direct Mw = 7.0 instead of direct Mw = 7.1 from Jackson et al. (1979). Source mechanisms added as well;
- from Spindler et al. (1997), evid 680306 and 679932 have direct Mw = 5.44 and 5.42 instead of proxy Mw = 5.54 and 5.48, respectively. Source mechanisms added as well;
- from Taymaz et al (1991a), evid 858461, 826342 and 810456 have updated direct Mw = 6.0, 7.0, 5.7, respectively, instead of direct Mw = 6.1, 7.2 and 5.8, respectively, from North (1977). Source mechanisms added as well;
- from Yılmaztürk and Burton (1999), evid 784339, 782114, 780154, 730797 have updated direct Mw = 6.3, 5.8, 5.5, 5.4 respectively, instead of proxy Mw = 6.2, 5.3, 5.4, 5.5. Source mechanisms added as well;
- from Taymaz and Price (1992), evid = 784361 has an updated direct Mw = 5.5 instead of a proxy Mw = 5.7. Source mechanism added as well;
- from McMullen (1985), evid = 776904 has an updated direct Mw = 5.8 instead of a proxy Mw = 5.9. Seismic moment and source mechanism from Fujita et al (1990);
- from Kao and Chen (1995), added direct Mw for 17 earthquakes in the Kuril-Kamchatka arc (evid 864902, 852862, 853361, 847380, 847389, 846123, 826015, 804095, 800341, 779780, 777414, 770242, 754242, 737585, 731548, 728825, 724162). The magnitude changes are all within 0.3 magnitude units but for evid = 847380 (direct Mw = 5.49 instead of proxy Mw = 6.17) and evid

800341 ((direct Mw = 5.13 instead of proxy Mw = 5.63). Source mechanisms added as well;

- from Frederich et al. (1988), evid 771020 has a direct Mw = 5.3 instead of a proxy Mw = 5.7. Source mechanism added as well;
- from Hatanaka and Takeo (1989), evid = 730371 has a direct Mw = 6.3 instead of a proxy Mw = 6.4. Source mechanism added as well;
- from Wiens and Stein (1984), evid = 864472, 829595, 723396 and 709472 have direct Mw = 5.86, 5.79, 5.71, 5.57 instead of a proxy Mw = 5.67, 5.71, 5.71 and 5.89, respectively. Source mechanisms added as well;
- from Buforn et al. (1988), evid = 864498 and 808624 have direct Mw = 5.85 and 5.34 instead of a proxy Mw = 5.65 and 5.58, respectively. Evid = 790313 has an updated direct Mw = 5.57 instead of a direct Mw = 5.9 from Muller (1983);
- from Parvez and Ram (1996), evid = 863756 has direct Mw = 6.6 instead of proxy Mw = 6.8
- from Huang and Solomon (1988), evid = 845209 and 751094 have direct Mw = 5.67 and 5.9 instead of a proxy Mw = 5.55 and 5.67, respectively. Source mechanisms added as well;
- from Pinar et al. (1996), evid = 833573 has an updated direct Mw = 7.3 instead of a direct Mw = 7.4 from Stewart and Kanamori (1982). Source mechanisms added as well;
- from Abers et al. (1997), added direct Mw for evid 830123, 826964, 799772, 788524, 760101, 760115, 736783 and 708658. The magnitude changes are all within 0.2 magnitude units. Source mechanisms added as well;
- from Baker et al. (1993), evid = 821091 and 785381 have direct Mw = 5.5 and 5.2 instead of a proxy Mw = 5.39 and 5.36, respectively. Source mechanisms added as well;
- from Tréhu et al. (1981), evid 797091 has a direct Mw = 5.7 instead of a proxy Mw = 5.55;
- from Walker et al. (2003), evid = 816697 has a direct Mw = 5.5 instead of a proxy Mw = 5.53. Source mechanisms added as well;
- from Suarez et al. (1983), evid = 813767 and 779337 have direct Mw = 5.8 and 5.6 instead of a proxy Mw = 5.5 and 5.7, respectively. Source mechanisms added as well;
- Evid = 777750 and 752200 have an updated direct Mw = 7.62 and 7.04 instead of 7.59 and 6.72, respectively, after correcting typos in the seismic moment originally inserted from Zakharova and Chepkunas (1977);
- from Eyidogan and Jackson (1985), evid 811616 and 798506 have an updated direct Mw = 6.8 and 7.23, respectively, instead of direct Mw = 6.7 and 6.9, respectively, from North (1977). Evid = 796798 has direct Mw = 5.5 instead of proxy Mw = 5.56. Source mechanisms added as well;
- from Kebede et al. (1989), evid 811667 and 809619 have direct Mw = 5.8 and 5.7 instead of proxy Mw = 6.1 and 5.4, respectively. Source mechanisms added as well;
- from Grimison and Chen (1986), evid = 804189 has an updated direct Mw = 6.0 instead of a direct Mw = 6.1 from North (1977). Source mechanism added

as well;

- from Wang et al. (1991), evid = 715117 has a direct Mw = 5.8 instead of a proxy Mw = 6.1. Source mechanisms added as well;
- from Pondrelli et al. (2001), evid 713751, 713914, 708347, 708348 and 708560 have direct Mw instead of proxy Mw. The magnitude changes are between -0.1 and -0.24 magnitude units. Source mechanisms added as well;
- from Louvari et al. (2001), evid = 534670 has an updated direct Mw = 5.2 instead of a proxy Mw = 5.55. Source mechanism added as well;
- from Kiratzi and Louvari (2003), evid = 502314 has an updated direct Mw = 5.3 instead of a proxy Mw = 5.3. Source mechanism added as well;
- from Pondrelli et al. (1999), evid 391124 has an updated direct Mw = 5.2 instead of a proxy Mw = 5.9. Source mechanism added as well;
- from Ghose et al. (1998), evid = 291467 has a direct Mw = 5.9 instead of a proxy Mw = 6.3. Source mechanism added as well;
- from Tape et al. (2015), evid = 1742778 has a direct Mw = 4.9 instead of a proxy Mw = 5.2. Source mechanism added as well;
- from Yolsal-Çevikbilen and Taymaz (2012), evid = 7159973 has direct Mw = 5.53 instead of a proxy Mw = 5.55. Source mechanism added as well;
- from Donner et al. (2013), evid = 7349696 has a direct Mw = 5.1 instead of a proxy Mw = 5.1. Source mechanism added as well;
- from Minson et al. (2007), evid = 1737488 has an updated direct Mw = 5.3 instead of a proxy Mw = 5.6. Source mechanism added as well;
- Evid = 1738466 has an updated proxy Mw = 5.6 based on mb instead of proxy Mw = 6.2 based on MS;
- from Stich et al. (2003), evid 1741740 has a direct Mw = 5.1 instead of proxy Mw = 5.1. Source mechanism added as well;
- from Ross et al. (2015), evid 2298998 has a direct Mw = 5.0 instead of proxy Mw = 5.3. Source mechanism added as well;
- from Sharma et al (2014), evid = 12776554 has a direct Mw = 5.1 instead of proxy Mw = 5.3;
- from Zheng et al. (2020), evid = 15742574 has a direct Mw = 6.3 instead of proxy Mw = 6.7. Source mechanism added as well;
- from Martín et al (2015), evid 608001961 has a direct Mw = 5.0 instead of proxy Mw = 5.2. Source mechanism added as well;

- Events added/deleted following further review of the bibliographic search (Lee and Engdahl, 2015):

  - from Doser et al. (2002), added evid = 864199 and 738167 with both direct Mw = 5.7. Source mechanisms added as well;
  - from Huang and Solomon (1988), added evid = 824131 and 771529 with direct Mw = 5.5 and 5.7, respectively. Source mechanisms added as well;
  - from Hashizume (1973), added evid = 788828 with direct Mw = 5.0. Source mechanism added as well;
  - from Buforn et al. (1988), added evid = 789668, 773446 and 648716 with direct Mw = 5.52, 5.42 and 5.55, respectively;

- from Anderson et al. (1993), added evid 869382 and 781200 with direct Mw = 5.85 and 5.7, respectively. Source mechanisms added as well;
- from Webb and Anderson (1998), added evid 750014 and 735096 with direct Mw = 5.8 and 5.4, respectively. Source mechanisms added as well;
- from Hasegawa et al. (1979), added evid = 727630 with direct Mw = 5.4. Source mechanism added as well;
- from Patton and Zandt (1991), added evid 875624 and 872679 with direct Mw = 5.2 and 5.0, respectively. Source mechanisms added as well. Deleted evid 636282 and 646154 after considering their direct Mw = 4.7 and 4.4, respectively. These events had proxy Mw = 5.2 and 5.3, respectively;
- from Doser and Smith (1982), added evid 863670, 849333 and 761535 with direct Mw between 5.9 and 5.2;
- from Abe (1978), added evid = 709966 with direct Mw = 5.5. Source mechanisms added as well;
- from Bent and Hasegawa (1992), added evid 802630, 498660, 450613 and 410102 with direct Mw 5.0-5.1. Source mechanisms added as well;
- from Pondrelli et al. (1999), added evid 540706 and 414569 with direct Mw = 5.1. Source mechanisms added as well;
- deleted evid 853275 and 759364 after considering the direct Mw = 4.6 and 4.5, respectively, by Hermann (1979). Both events were listed with proxy Mw = 5.1;
- from Imprescia et al. (2012), added evid = 608518 with direct Mw = 5.0. Source mechanism added as well. Deleted evid 558893 after considering the direct Mw = 4.8. The event was listed with proxy Mw = 5.25;
- deleted evid 601551788 and 601561357 after considering the direct Mw = 4.7 and 4.8, respectively, by Donner et al (2015). The events were listed with proxy Mw = 5.2 and 5.3, respectively;
- from Stich et al. (2003), added evid 551519, 484527 and 412598 with direct Mw = 5.0. Source mechanisms added as well.

- Updates following the review done in the Rebuild project (Storchak et al., 2017):

  - Evid 13825954 has been moved to the Supplementary catalogue as its proxy, based on mb instead of MS, has large uncertainty. The MS was erroneously obtained from readings that belong to close event = 14092590 (Mw = 7.8 from GCMT);
  - deleted evid 17308392 as it has been merged with evid 798256;
  - deleted evid 1656082 as it has been merged with evid 1718616;
  - deleted evid 11906317 as, after reassessment along with close event 12696659, it does not meet the selection criteria of the ISC-GEM Catalogue;
  - deleted evid 16874517 as it has been merged with evid 16718055;
  - reassessed the Mw proxy for 26 earthquakes that occurred between 1981 and 1999. For ten events (evid 629928, 626279, 562542, 362906, 341121, 185730, 137617, 102775, 99991, 85331) the new Mw proxy is based on mb instead of MS and the magnitude changes are within 0.5 magnitude units but for evid 99991, 626279 and 629928, where the magnitude is between 0.7 and 0.8 magnitude units smaller than previous values. For the other 16 events (evid

539698, 529109, 517380, 488638, 480644, 446348, 443059, 428578, 386064, 347624, 334035, 322180, 322901, 260735, 940369, 1655244) the Mw proxy is based on recomputed MS and the magnitude changes are within 0.3 magnitude units.

- Additional updates:
    - added evid = 908215 with proxy Mw = 5.9;
    - evid 604041862, 609948332, 605130587, 605642941, 605737143 have updated proxy Mw based on mb instead of MS. The magnitude changes are between 0.2 and 0.4 magnitude units.

## Digitizing BCIS bulletins

The major source of phase data for the ISC-GEM Catalogue before the beginning of the ISC Bulletin started in 1964 is the International Seismological Summary (ISS 1918-1963). The ISS has been entirely digitized and the earthquakes with ISS data have been assessed for the ISC-GEM Catalogue. Another source of phase data pre-ISC Bulletin is the Bureau Central International de Seismologie (BCIS, 1933-1968) that was produced in France in parallel to the ISS production of the ISS in United Kingdom. The BCIS lists absolute arrival times of large and small earthquakes around the globe and in some years appears to list station data for more earthquakes than the ISS. Hence, in this year project we started digitizing the BCIS content for earthquakes that occurred in the 1950s that are not listed in the ISS or have no data in the ISS. Such task, although time consuming, has the potential to add several earthquakes that had no data before (hence not processed for the ISC-GEM Catalogue) and improve the composition of the ISC-GEM Catalogue in years where the ISS censored several earthquakes form its listing, particularly between 1953 and 1959.

At the end of this project year, we digitized station data for over 7500 earthquakes in the 1950s, as shown in Figure 7. Along with phase data for location we will start in 2021 to add amplitude data (mostly surface wave measurements) to select candidate earthquakes for the ISC-GEM Catalogue. At the end of Year IV of the Advancement Project we expect to add several hundred earthquakes to the ISC-GEM Catalogue after processing selected events that complement BCIS phase data with amplitude measurements from individual station bulletins (Di Giacomo et al., 2015a). At the same time, we will continue to digitize BCIS data pre-1950 and attempt to add earthquakes in 1960-1963 that were not reported in the ISS.

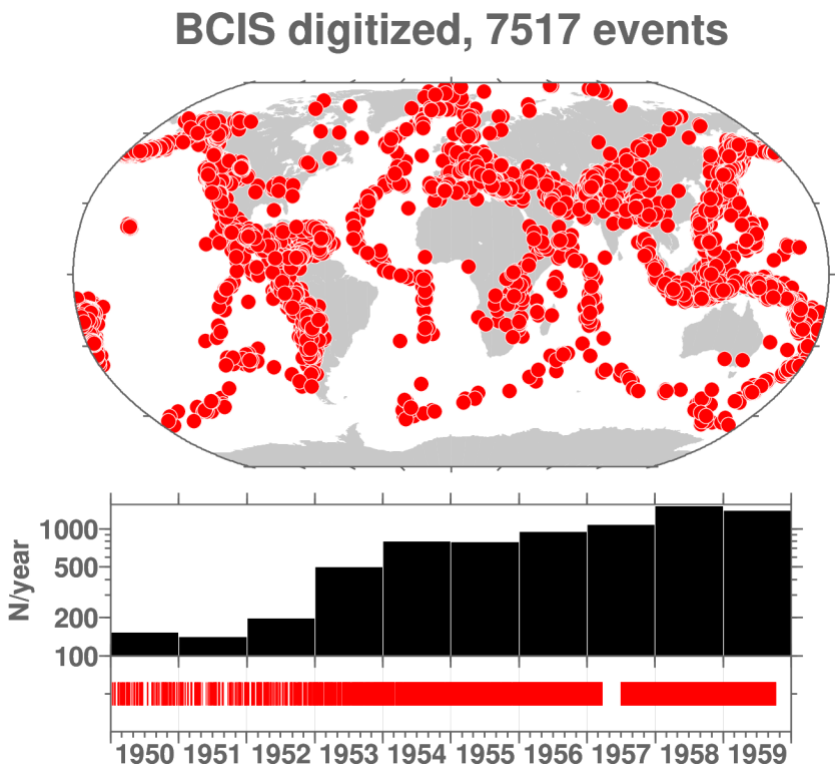


***Fig. 7****: Top: map showing the location of the BCIS earthquakes for which we digitized phase data in the 1950s; Bottom: Timeline and number of earthquakes per year.*

## New version of the ISC-GEM catalogue

The updated plot of the time-magnitude distribution of the ISC-GEM main catalogue 1904-2017 is shown in Figure 8 (for comparison with previous version see Figure 25 of Di Giacomo et al., 2018).

The earthquakes that occurred in 2017 extend the same magnitude distribution that we can observe in recent years and add significant earthquakes to the catalogue. The biggest difference with the previous version is for the period 1991-1999, where we added nearly 1900 earthquakes. Note that the ISC-GEM Catalogue cannot be complete down to 5.0 as the only earthquakes added below 5.5 are continental one as defined earlier in this document.

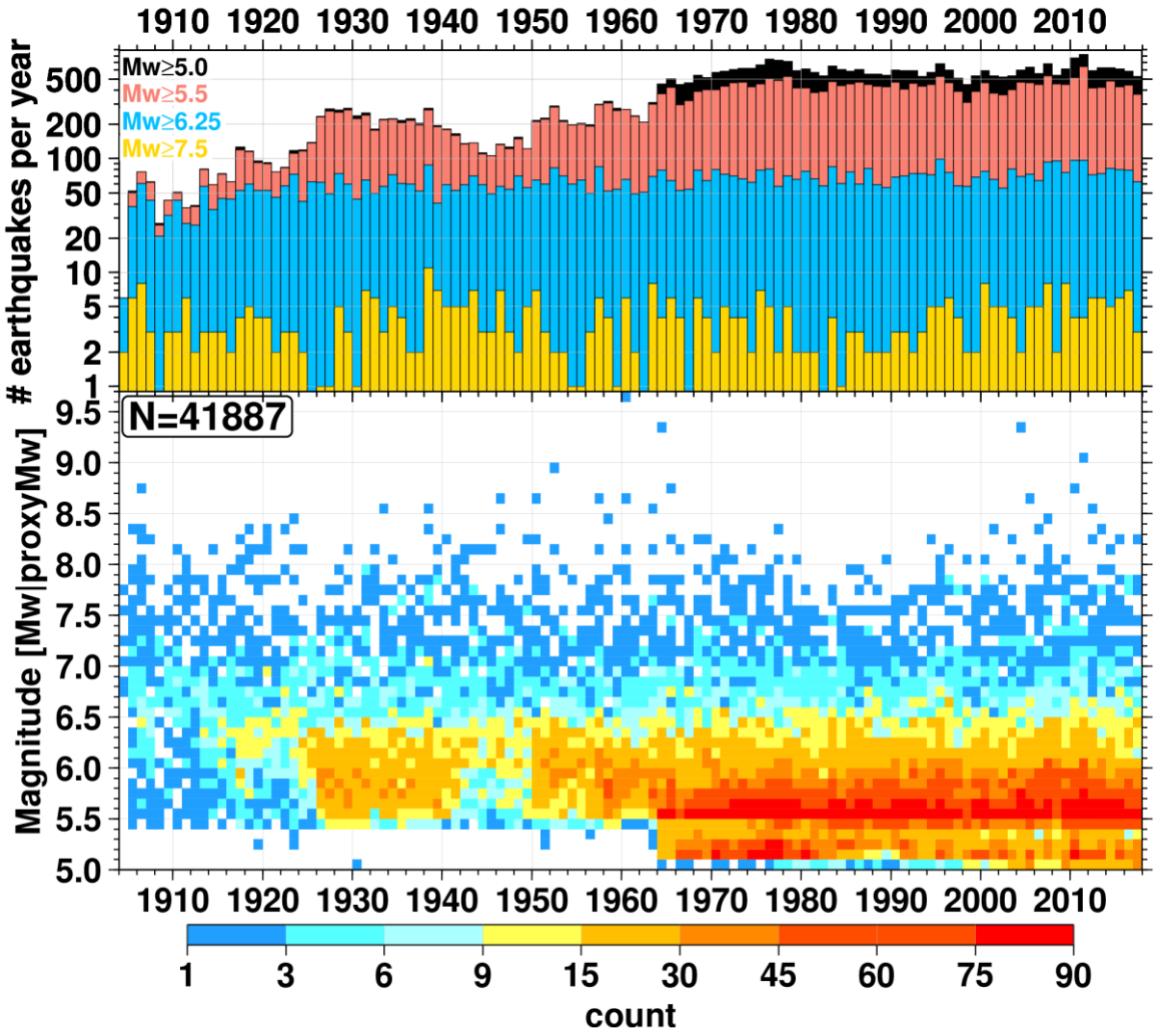


***Fig. 8****: Top: cumulative annual number of earthquakes with Mw ≥ 5.0 (black), Mw ≥ 5.5 (red), ≥ 6.5 (blue) and ≥ 7.5 (yellow); Bottom: time-magnitude distribution color-coded in cells of 0.1 Mw units for each year of the ISC-GEM Catalogue.*

## Summary

During the 3rd year of the ISC-GEM Advancement project we relocated ~1900 earthquakes that occurred between 1991-1999 and added 543 earthquakes in 2017. In addition, we sourced from the literature 448 source mechanisms for earthquakes with no GCMT solution and added direct $M_0$ values (hence of Mw) for 322 earthquakes. Improvements to earthquakes previously listed were done by updating the magnitude and/or location for about 400 earthquakes. We also reprocessed 900 earthquakes between 1920 and 1945 after adding data (mostly surface wave amplitude and period measurements for MS computation) from individual station bulletins donated to the ISC by the University of Stuttgart. As result of the data added, we also list new 17 earthquakes that were not selected before.

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- **Project data**:

The project data have been made openly available. The Ver.8 of the ISC-GEM catalogue (http://doi.org/10.31905/D808B825) is available at the ISC website (http://www.isc.ac.uk/iscgem/download.php), distributed under the terms of the CC-BY-SA/3.0 license.

In addition, the underlying individual station data (arrival times, amplitudes, and periods at individual seismic stations) obtained during the project for 1964-1917 period are released as part of relevant events in the ISC Bulletin. For the 1904-1963 period, we plan such release during 2021-2022.

- **Bibliography of publications resulting from work performed under the award**:

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Signed by D.A. Storchak,
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